REIONIZATION OF THE UNIVERSE
INDUCED BY PRIMORDIAL BLACK HOLES.

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Abstract:

In this paper I will discuss the possibility of a reionization of the Universe due to the photons emitted by evaporating primordial black holes (PBHs); this process should happen during the last stages of the PBHs life, when the particle emission is very intense. I will study the time evolution of the ionization degree x, of the plasma temperature T_e and of the photon number density n_γ characterizing the Universe after the recombination epoch: a system of coupled differential equations for these variables is solved in an analytical way, by assuming, as a photon source, PBHs having an initial mass $M \sim 10^{14}$ g. I will also take into account the PBH emission of quarks and gluons jets, which should be expected from PBHs having a temperature $T > \Lambda_{QCD}$. The results I obtain prove that such a kind of reionization is possible, being able to increase the ionization degree of the Universe from a value $x = 0.002$ (just after the recombination) to values near 1 (when the black holes evaporation ends); in the same time, the rise of the plasma temperature T_e is limited by powerful cooling effects; therefore, such a reionization model does not predict an excessive distortion of the Cosmic Microwave Background (CMB) spectrum, in agreement with the experimental FIRAS data on the comptonization parameter y_c ($y_c < 2.5 \times 10^{-5}$).

1. PBH QUANTUM EVAPORATION AND PHOTON EMISSION SPECTRUM.

The possibility that the Universe was reionized after the recombination is strongly suggested by many experimental evidences as, for instance, the Gunn Peterson test [1]. The causes of such a reionization for the Universe are unclear and, in general, a complete theory describing this phenomenon is not yet available.

In Refs. [2, 3] I discussed a possible reionization mechanism based on the quantum evaporation of primordial black holes; why primordial? Due to the inverse proportionality existing between the mass and the temperature of an evaporating black hole, we should expect a significant radiation emission only for small mass ($M << M_\odot$) BHs, therefore formed immediately after the Big Bang. The nature of the emitted particles obviously depends on the blackbody temperature of the PBHs: typically, BHs having a mass larger than 10^{17} g emit massless particles only, like photons, neutrinos and, may be, gravitons.

In Refs. [4, 5] Carr, Mac Gibbon and Webber showed that the quarks and gluons jets production should not be neglected when the BH mass falls below 10^{14} g and the temperature T becomes larger than the confinement scale Λ_{QCD}: in this case, the Hawking emission rate for particle production becomes [6]:

$$\frac{dN_x}{dt dE} = \sum_j \int_0^{+\infty} \frac{\Gamma_j(Q,T)}{2\pi\hbar} \left(exp\frac{Q}{T} \pm 1 \right)^{-1} \frac{dg_{jx}(Q,E)}{dE} \, dQ; \qquad (1.1)$$

here the signs $\pm$ respectively refer to fermions and bosons; Γ is the absorption probability of the emitted species [7], x and j respectively refer to the final and to the directly emitted particles and the last factor expresses the number of particles with energy in the range $(E, E + dE)$ coming from a jet having an energy equal to Q; the fragmentation function g_{jx} reads as follows [6]:

$$\frac{dg_{jx}(Q,E)}{dE} = \frac{1}{E} \left(1 - \frac{E}{Q} \right)^{2m-1} \theta(E - km_h c^2), \qquad (1.2)$$

where m_h is the hadron mass, k is a constant $O(1)$ and m is an index equal to 1 for mesons and 2 for baryons.

2. THE TIME EVOLUTION OF THE IONIZATION DEGREE AND OF THE PLASMA TEMPERATURE FOR A REIONIZED UNIVERSE.

As I discussed in Refs. [2] and [3], the basic equations that control the time evolution of the ionization degree x and of the plasma temperature T_e are [8]:

$$\frac{dx}{dt} = t_{pi}^{-1} + t_{coll}^{-1} - t_r^{-1}, \qquad (2.1)$$

and

$$\frac{dT_e}{dt} = -2\frac{\dot{R}}{R}T_e - \frac{T_e}{(1+x)}\frac{dx}{dt} + \frac{2}{3(1+x)}(\Gamma - \Lambda), \qquad (2.2)$$

where t_{pi}^{-1}, t_{coll}^{-1}, t_r^{-1} are, respectively, the photoionization, the collisional and the recombination rates. In eq. (2.2), the heating Γ mainly comes from the photoionization process

while the cooling Λ takes into account the contributions due to the recombination, the collisional and excitation processes, the Compton scattering and to the expansion of the Universe: a detailed discussion of these effects can be found in Ref. [3].

Both the equations (2.1) and (2.2) explicitly contain the photon number density n_γ, whose time evolution can be written as follows [2, 3]:

$$\frac{\partial n_\gamma(\omega,t)}{\partial t} + \frac{\dot{R}}{R} \frac{\partial n_\gamma(\omega,t)}{\partial \omega} \omega_{NOR} - 2 \frac{\dot{R}}{R} \frac{n_\gamma(\omega,t)}{\omega} \omega_{NOR} =$$

$$= \left(\frac{dn_{\gamma R}}{dt} - \frac{dn_{\gamma PI}}{dt} \right) + \frac{2}{\omega} \frac{d\omega}{dt} [n_{\gamma PI} - n_{\gamma R}] + \frac{\partial n_{\gamma PR}}{\partial \omega \partial t} \omega_{NOR}; \qquad (2.3)$$

here $n_{\gamma PI}$, $n_{\gamma R}$ are the photon number densities respectively involved in the processes of photoionization and recombination and ω_{NOR} is a normalization factor, equal to 10^{-6}. The last term in eq. (2.3) is the contribution of the photon source, in our case a number n_{PBH} of evaporating primordial black holes. A rough estimate of this parameter can be obtained by considering the following relations:

$$\rho_i \sim \frac{<M> n_{PBH}}{R^3(t_{in})}, \qquad (2.4)$$

where $<M> \sim 10^{14}$ g and

$$R(t_{in}) \sim R_0 \ (t_0/t_{in})^\alpha; \qquad (2.5)$$

here $R_0 = 1.25 \times 10^{28}$ cm $= 1.4 \times 10^{10}$ lyr in a typical cosmological model [9] and $\alpha = -0.5$. Then, if one assumes for the PBHs density a behaviour that approximately scales as a power with exponent $2/3$ of the time, the present density parameter Ω_{PBH} varies in a range:

$$\Omega_{PBH} = \frac{\rho_{0PBH}}{\rho_{cr}} = 1.12 \times 10^{-12} \div 1.65 \times 10^{-8}; \qquad (2.6)$$

this rough estimate reproduces quite well the present experimental upper limit for Ω_{PBH}, coming from the CMB constraints [4]: $\Omega_{PBH} \leq (7.6 \pm 2.6) \times 10^{-9} \ h^{(-1.95 \pm 0.15)}$.

3. THE NUMERICAL SOLUTION OF THE DIFFERENTIAL EQUATION SYSTEM: RESULTS AND CONCLUSIONS

A detailed discussion of the analytical solution of eqs. (2.1), (2.2) and (2.3) can be found in Refs. [2, 3]; here I want only to recall the main results coming from this analysis.

In figs. 1 and 2 I plotted the behaviour of the ionization degree x and of the plasma temperature T_e for a reionization redshift $z_R = 30$: as one can see, the BH-induced reionization of the Universe is indeed possible but it is partial only; a quite relevant effect

is obtained for an evaporation redshift corresponding to $z_R \leq 30$, while for higher values of z_R the process of PBHs quantum evaporation cannot produce an appreciable phenomenon of reionization.

The plasma heating level is a fundamental test for all the reionization models: in fact, an excesssive heating would contradict the FIRAS upper limit on the comptonization parameter y_c ($y_c < 2.5 \times 10^{-5}$). In our case, the plasma heating is limited by a powerful cooling: in eq. (2.1) the t_{pi}^{-1} term is suppressed and the t_r^{-1} term is enhanced [3].

Finally, in this model, we have none significant suppression of the CMB temperature fluctuations on small angular scales: Bond and Efstathiou [10] and Vittorio and Silk [11] suggest that a reionization at $z_R \sim 50$ could indeed suppress these fluctuations that, following the predictions of the CDM models and texture scenarios [12], would result too large; but, as I told, in my model the reionization for $z_R > 30$ is uneffective.

The PBHs formation time should be put very far in the past: considering the jet emission contribution in the photon spectrum, I can obtain a well balanced reionization process (i.e. a high ionization degree without an excessive plasma heating) only for a formation time contemporary to the Big Bang and for an initial density $\rho_i = 10^{17} \div 10^{24} g/cm^3$, corresponding to a present density parameter $\Omega_{PBH} \sim 1.12 \times 10^{-12} \div 1.65 \times 10^{-8}$.

The behaviour of x can be approximated by an exponential function: this result justifies my analysis of Ref. [13], where I studied the consequences of an exponential reionization of the Universe on the polarization of the Cosmic Microwave Background.

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